6 Dynamic Droplets

> *… a computer of such infinite and subtle complexity that organic life itself shall form part of its operational matrix.* (Adams, 1995, p.129)

6.1 Overview

This chapter establishes the Bütschli droplet system as an experimental model to interrogate the technological potential of vibrant matter. The original recipe developed by zoologist Otto Bütschli in 1892 (Bütschli, 1892) was recreated to fully characterize the system. A series of around 300 experiments were conducted in a laboratory setting under the supervision of Associate Professor Martin Hanczyc at the Center for Fundamental Living Technology (FLinT), at the University of Southern Denmark. Each experiment was photographically recorded using a Nikon Eclipse TE2000-S inverted microscope with a Photometrics Cascade II 512 camera and in-house software. Having become familiar with the limits and range of the dynamic chemical system, ways to influence its outputs were explored and examined from technical and graphical perspectives. This could be achieved by manipulating internal and external conditions of the system, and suggested that Bütschli droplets could be applied in both technological and drawing contexts. Finally, the ontological and epistemological implications of a non-mechanical[40] technology were considered for its potential application within architectural design-led experiments.

6.2 Identifying a Suitable Model System for Vibrant Matter

A testable model for vibrant matter that is relevant to architectural design practice needs to exhibit observable behaviours at the human scale. My literature survey identified 'dissipative' systems (Prigogine, 1976; Prigogine and Stengers, 1984; Prigogine, 1997) as suitable candidates, since they exist at many scales and exhibit lifelike properties, which include cosmic phenomena (Prigogine, 1997; Smolin, 1997; Langton, 1980), weather patterns (Prigogine and Stengers, 1984; Prigogine, 1997) and even microscale events (Prigogine, 1997; Max Planck Institute for Dynamics and Self-Organization, 2003–2013). Dissipative systems have recognizable forms of organization such as vortices, and although they possess structure, they are not objects but are shaped by a constant flow of energy and matter (Prigogine, 1972). Dissipative structures therefore possess both object-centred and process-led qualities.

40 I also use the term 'non-linear technology' owing to the Deleuzian concepts that shape process-led events (DeLanda, 2000).

Even before Prigogine coined the term 'dissipative structures', such far from equilibrium self-organizing chemical systems have been studied since the Enlightenment in phenomena such as Glauber's chemical gardens (Glauber, 1651), Runge's dynamic chemical patterns (Runge, 1850), Moritz Traube's 'artificial' plant cells (Traube, 1867), Liesegang's self-organizing rings (Liesegang, 1869), Otto Bütschli's protozoan-like chemical system (Bütschli, 1892), Stephane Leduc's 'fungal' osmotic structures (Leduc, 1911, pp.123–146) and Belousov and Zhabotinsky's vibrant periodic chemistry (Belousov, 1959; Zhabotinsky, 1964). More recently, a range of different species of dynamic droplets (Hanczyc, 2007; Toyota, 2009) and iCHELLS (Cooper et al, 2011)[41] have also been observed to embody lively processes associated with living systems. Each was demonstrated experimentally and explored to establish their suitability as a model system for vibrant matter. The outcome of these experimental demonstrations was that dynamic droplet systems were a preferred experimental model for vibrant matter.

6.3 Dynamic Droplets as Vibrant Matter

A range of dynamic droplet systems exhibited striking, immediate and sometimes sustained effects that were observable at the human scale, which appeared suitable for use in an architectural design context. It was therefore important to identify a species that could be safely applied within social settings.

Dynamic droplets are self-assembling agents that are based on the chemistry of oil and water. They arise from a spontaneous field of self-organizing energy and can exist as oil droplets in a water medium, or water-based droplets in an oil medium. They exist as a range of different kinds of 'species' being composed from different recipes. Where oil/water interfaces occur, there is a spontaneous self-assembly of molecules owing to the chemical basis for energy exchange at the droplet interface. The consequences of mass interactions are observed in the system as emergent phenomena that typically exhibit lifelike behaviour such as movement. Even when the initial conditions are the same, the various droplet species show a range of possible types in any given environment because of the emergence in the system, and these can be characterized. Dynamic droplets can be influenced by internal and external factors and, therefore, are suitable systems for engaging with design principles. Dynamic droplets are restless, inherently creative agents that ceaselessly patrol and reposition their chemical networks. As dissipative structures, they throw out energy and materials to resist the decay towards equilibrium towards which they will eventually succumb in their mayfly-like existence, which lasts between several seconds to many weeks, depending on their chemical composition and context. It is

41 iCHELLS are 'inorganic chemical cells'.

possible to read the activity of a dynamic droplet through the environmental traces that are left as microstructures and crystals that may become the site for further droplet activity, resulting in complex constructions that can be seen with the naked eye. A range of preparations, including decanol/decanoate oil in water droplets and the Bütschli water in oil droplet system, were explored in a laboratory setting where it was possible to make a cursory assessment of the systems with respect to their technological potential and their suitability for architectural design contexts. The Bütschli system was examined in further detail as it produced the most vigorous agents from inexpensive ingredients.

6.4 Characterizing the Bütschli Dynamic Droplet System

Otto Bütschli first described a dynamic water in oil droplet system using potash and olive oil as reactants, in which he observed the genesis of an ‘artificial’ amoeba with pseudopodia (cytoplasmic extensions) that behaved in a lifelike manner (Bütschli, 1892). His aim was to make a simplified experimental model to explain the plasticity of body morphology and movement, based purely on physical and chemical processes such as fluid dynamics and changes in surface tension (Belousov, 1959). Bütschli’s original experiment was documented with hand drawings. Although various research groups are investigating other dynamic chemical systems that use amphiphiles, such as reverse micelles (water in oil droplets stabilized by a surfactant) (Pileni, 2006) and the behaviour of oil droplets in aqueous media (Hanczyc et al, 2007; Toyota et al, 2009), no photographic documentation of the Bütschli system appears to exist in the contemporary literature.

For vibrant matter to be applied to problem solving, it needs to be operationalized. The Bütschli system therefore requires full characterization before its technological potential can be evaluated. The behaviour and morphology of this system was observed under light microscope in approximately 300 replicate experiments. It qualifies as an example of ELT through its formation of discrete dynamic droplets during a variable window of time (from 30 s to 30 min after the addition of alkaline water to the oil phase) that are characterized by their lifelike behaviour patterns. Self-organizing patterns are observed during this dynamic, embodied phase that provide a means of introducing temporal and spatial order into the system and offer the potential for further chemical programmability.

6.4.1 Bütschli System Preparation

The experimental design followed was a modern interpretation of Bütschli’s original ingredients (potash and fresh olive oil). A 0.2 ml drop of 3 M sodium hydroxide was added to olive oil in a 3 cm diameter petri dish, which was filled to a depth of 0.5 cm with extra virgin olive oil. These ingredients combine through a saponification reaction, in which the trigylerides of the olive oil are cleaved to produce free fatty acids and glycerol. The main ingredient of olive oil is oleic acid, which constitutes around 61.09% to 72.78% depending on the source (Matthäus and Özcan, 2011). The same brand of oil, Monini extra virgin from Spoleto, Italy, was used exclusively in this experiment, although it is not known whether different bottles came from the same production batch. All ingredients were used at room temperature. Systems that included a titration of sodium hydroxide were also performed.

Controls included adding a 0.2 ml drop of water to a 3 cm diameter petri dish filled to 0.5 cm deep with olive oil, and also by adding 0.2 ml 3 M sodium hydroxide to a 3 cm diameter glass-bottomed petri dish filled to 0.5 cm deep with canola oil (rapeseed), from Cargill Oil Packers, which is around 85% oleic acid (Zarinabadi, Kharrat and Yazdi, 2010). The behaviour of the system was characterized in detail using a Nikon Eclipse TE2000-S inverted microscope with a Photometrics Cascade II 512 camera and in-house software.

6.4.2 Bütschli System General Observations

The breaking up of the alkaline droplet in the oil could be clearly seen with the naked eye, as shown in Fig. 6.1, Fig. 6.2 and Movie 6.1. The active chemical field produced smaller droplets whose diameters splayed variably between a millimetre and a centimetre, generating turbid deposits of soap in the dish. In the case of the water in canola oil control, no breaking up of the droplet was observed, and in the case of adding 3 M sodium hydroxide to canola oil,[42] the alkali droplet dispersed into smaller droplets but did not show the asymmetric pattern progression, dynamism or production of material observed in the Bütschli system.

Additional experiments were also carried out under the same conditions to establish the concentration range of sodium hydroxide that would produce the characteristic Bütschli pattern formation, which was established to lie within the 3 M to 5 M range. At concentrations of less than 3 M, the droplets possessed little dynamism or visible crystal formation and, although the droplet gradually broke up over a course of several minutes (around 3–10 min) to form droplets, the characteristic sequence of patterns typically observed at higher molarity was not observed. At concentrations of greater than 5 M, the system quickly became inert and instantly formed a crystal layer

42 Sodium hydroxide, at 0.5 M increments from 1–5 M, was used to test the reactivity of the canola oil control but the droplets produced did not produce lifelike behaviours across the whole spectrum of this range. The optimum range for the break-up of surface tension in canola oil was 3 M, which produced most (non-dynamic) droplets. This concentration of sodium hydroxide was therefore used as a standardized 'control' against which to compare the reactivity of the Bütschli system.

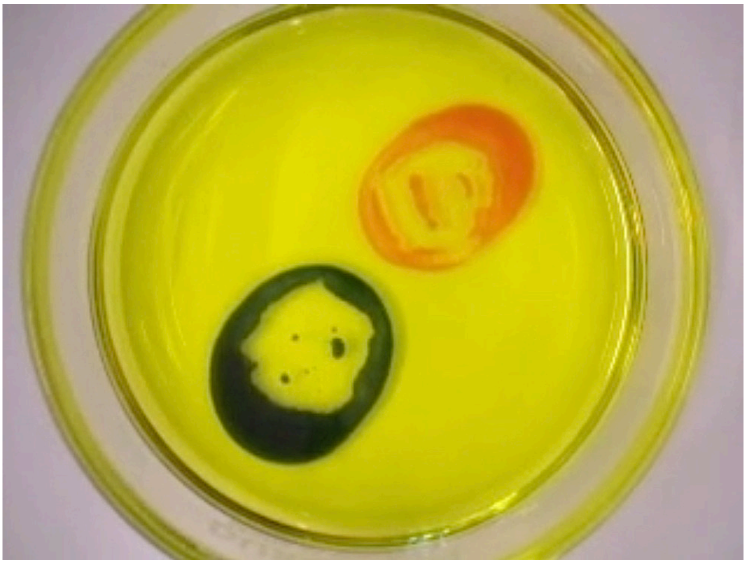

Figure 6.1: High-energy field: Bütschli droplets form when droplets of 3 M sodium hydroxide containing 1% v/v food colouring (red and blue) are added to a 3.5 cm glass dish of olive oil. Movie still, courtesy Martin Hanczyc, February 2009.

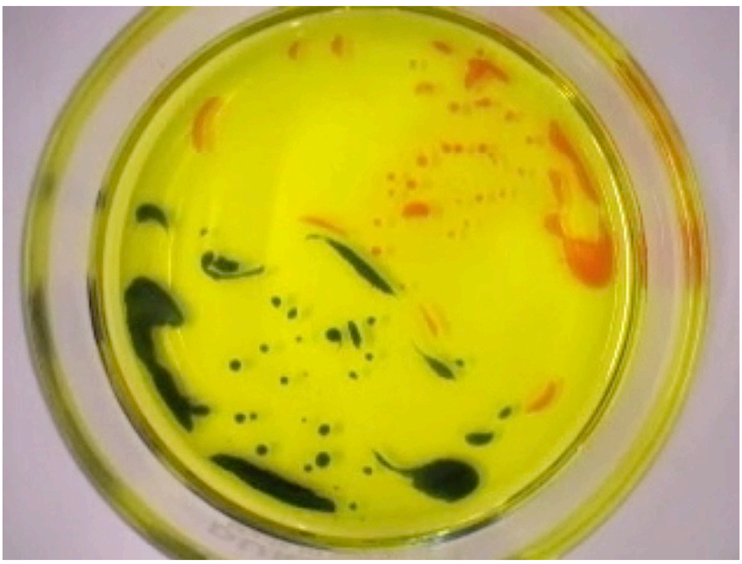

Fig 6.2: Bütschli droplets are spontaneously produced when fields of olive oil and alkali overlap. Movie still, courtesy Martin Hanczyc, February 2009.

at the oil/water interface, quenching the reaction and preventing the appearance of dynamic patterns.

When canola oil was used as the medium for sodium hydroxide in the active range for pattern production seen in the Bütschli system (3–5 M), the activating droplet broke up immediately into smaller, regular droplets in the oil field, but neither was any sequential organizing activity observed nor was any formation of product visible.

In the study group of experiments (0.2 ml 3 M sodium hydroxide added to extra virgin olive oil), the Bütschli system demonstrated a repeatable sequence of events with identifiable characteristics, recorded in still photography and movies. The Bütschli droplets were observed and studied in a similar manner to that is currently used to study and report on single-celled organisms such as protozoa or bacteria. No staining was necessary to observe the Bütschli droplets, due to their refractive index, and they ranged from the microscale to around a centimetre in diameter. The lifelike qualities of the Bütschli system were sufficiently striking to appropriate the use of a method of observation normally applied in a natural history context as useful for the study of the living characteristics of the system; the intention was to experimentally consider what kinds of organizing principles appeared to be at work in the transition from inert to living matter.

Bütschli droplets possess a primary metabolism, saponification, which spontaneously exists at the interface where strong alkali water and olive oil meet. This reaction releases both energy and products in the form of surfactants that modify the oil/water interface. This reaction is responsible both for the lowering of surface tension allowing the droplet to deform, and the flow of liquid, which results in droplet morphological fluctuations, movement and splitting. As the droplets move through their environment, they can consume the olive oil, processing it by the saponification reaction. In addition, they also use the alkali reactant within the droplet as fuel. Bütschli droplet movements last between several seconds to around 20 minutes. The activity of any particular droplet is not predictable and the success of creating the system is variable and possibly dependent on the quality of ingredients, with additives or degradation products in the olive oil decreasing the reactivity of the system. As the active droplet system progresses in time, the activity of the system slows as it approaches chemical equilibrium. Due to both the accumulation of inhibitory products and the consumption of fuel, the droplet eventually becomes inactive.

Typically, water droplets in oil self-assemble and do not dissipate due to their hydrophobic properties. However, in the Bütschli system, once the saponification reaction begins at the interface between the oil and water, the tension holding the droplet intact relaxes considerably and the droplet begins to distort and spread with increasing surface area. The droplets contain enough energy to split up into smaller droplets that are then able to move about in the olive oil environment. Notably, a control with water at neutral pH produces a spherical droplet in the olive oil that does not react, spread, split or behave like the alkaline droplet, and an alkaline droplet in canola oil splits into smaller droplets but without pattern formation.

In the reactive system, chemical potential is combined with physical instabilities and fluid dynamics, resulting in the movement of droplets associated with the production of a soapy crystalline deposit that spontaneously forms at the oil/water interface. Distinct phases characterize the progression of the ingredients from a highly energetic dissipative system to one that has reached equilibrium. During this progression, mass interactions are observed in the system as emergent phenomena where droplets and populations of droplets typically exhibit lifelike behaviour such as movement and the production of microstructures. Even when baseline conditions are uniform (temperature, pressure), these agents show a range of distinct characteristics that lend themselves to classification through distinct morphological and behavioural types that emerge from the self-organizing field (see Movie 6.2).

6.4.3 Stages of Bütschli Droplet Development

Osmotic growths like living things may be said to have an evolutionary existence, the analogy holding good down to the smallest detail. In their early youth, at the beginning of life, the phenomena of exchange, of growth, and of organization are very intense. As they grow older, these exchanges gradually slow down, and growth is arrested. With age the exchanges still continue, but more slowly, and these then gradually fail and are finally completely arrested. The osmotic growth is dead, and little by little it decays, losing its structure and its form. (Leduc, 1911, p.151)

In 1911, Stephane Leduc studied the behaviour of chemical solutions mixed together. He noted they produced strikingly lifelike results that he described as ‘evolutionary’. Leduc likened the behaviour of these chemistries to living systems, associating the behaviour of the chemistry with terminology that is normally associated with the ‘life cycle’ of an organism. This section builds on Leduc’s analogy and proposes a progression of events in the Bütschli system that alludes to possible consideration of and reflection on natural phenomena.

The stages of the lifespan of Bütschli droplets are summarized in Tables 6.1–6.4. They are described with reference to figures and movies that are organized into different phases of pattern progression and in their evolution through three distinct stages:

- Birth (0–5 min)
- Life (30 s–30 min)
- Death (0–30 min)

Table 6.1: Birth – from 0 s to 5 min following addition of sodium hydroxide droplet to olive oil phase

Figure ref.	Time after addition of alkali to oil phase	Movie	Pattern morphology	Comments
6.1	20 s	6.1	3.5 cm petri dish. Early movement dispersion of droplet and breaking up of the chemical wavefront due to changes in surface tension	Macroscopic view of Bütschli system
6.2	50 s	6.2	3.5 cm petri dish. Progressive movement and dispersion of droplet and breaking up of the chemical wavefront due to changes in surface tension	Same preparation as in Fig. 6.1 after the passage of 30 seconds
6.3	2 min 40 s	6.3	6 mm width of micrograph. Polarized field of 'fire' and 'ice'. The leading 'fire' edge is facing downwards and the trailing 'ice' edge is facing upwards in the micrograph	
6.4	8 s	6.4	6 mm width of micrograph. Turbulent, shell-like droplets that appear as a series of sequentially emerging manifolds	Some 'shells' collapse while others self-organize into droplets with lifelike properties such as movement

6.4.3.1 Birth: Field of Fire and Ice

When the alkaline droplet first breaks up in the oil field it self-organizes into a polarized, dynamic field with a characteristic appearance. The active, leading front end of the field moves outwards, away from the point at which the water droplet enters the oil field, and produces ripples as it moves through the oil media, producing a flame-like appearance. The leading edge is where oil molecules are consumed in the metabolism of the droplet. The trailing back end accumulates the product soap crystals that are swept backwards by the movement of the system, and in the case of sodium oleate, appear like ice crystals. In this initial dynamic and energetic stage, smaller droplets can break off from the moving front and then continue to display the same reactive motion. In the initial phase of self-organization, these fields look like moving islands of 'fire and ice', where it is possible to determine which direction the field is moving in by its morphology as shown in Fig. 6.3 and Movie 6.3.

Table 6.2: Life – primary morphologies from 0–30 s following addition of 0.2 ml droplet of sodium hydroxide to oil phase

Figure ref.	Time after addition of droplet to oil phase	Movie	Pattern morphology	Comments
6.5	2 min 30 s	6.5	300 micron width of micrograph. Motile droplet derived from the chaotic chemical field	Crystalline material is visible accumulating at the oil/water interface at the posterior pole
6.6	3 min	6.6	6 mm width of micrograph. Droplet with osmotic crystalline deposit	Crystalline material is visible as an osmotic microstructure attached to the droplet at its posterior pole
6.7 & 6.8	8 min	6.7	300 micron width of each micrograph. Osmotic structure seen with and without fluoroscopy in which the Bütschli droplet has just detached from an osmotic structure	Figs. 6.7 & 6.8 are the same structure
6.9	10 min	6.8	6 mm width of micrograph. Bütschli droplets produce deposits of sodium oleate at the trailing end of the motile droplet	Oleate crystals accumulate and extend to form fluid-filled ‘osmotic’ microstructures
6.10	2 min	6.9	6mm width of micrograph. Bütschli droplets before fusion	Fusion events are spontaneous and may be the generative agency for the production of compound, complex, osmotic microstructures

6.4.3.2 Birth: Shells

As the polarized field of self-organizing activity progresses, it starts to break up due to lowered surface tension and fluid dynamics as a consequence of saponification and the presence of soap crystals. The first recognizable ‘structures’ that appear are turbulent, shell-like morphologies and probably represent ‘dissipative’ structures that are literally throwing away energy to remain stable, as shown in Fig. 6.4 and Movie 6.4. These kinds of non-equilibrium phenomena were noted by chemist Ilya Prigogine (Glansdorff and Prigogine, 1971), who observed their occurrence in nature being characterized in structures such as snowflakes and vortices (cyclones and

Table 6.3: Life – primary behaviours from 0–30 s following addition of 0.2 ml droplet of sodium hydroxide to oil phase

Figure ref.	Time after addition of droplet to oil phase	Movie	Pattern morphology	Comments
6.11	8 min	6.10	300 micron width of micrograph. Two Bütschli droplets engage active interfaces generating various dynamic points of contact. They continue to make contact until the product (sodium oleate crystals) obstructs the interface between them	Interfaces between droplets persistently osculate
6.12	12 min	6.11	6 mm width of micrograph. Bütschli droplets 'mirroring' one another	
6.13	12 min	6.12	6 mm width of micrograph. A smaller Bütschli droplet is interfacing with a much larger one	The droplets remain in close proximity with each other until the build-up of soap crystals occludes the oil/water interface
6.14	8 min	6.13 & 6.14	6 mm width of micrograph. Bütschli droplets in a simple chain formation	Periodic oscillations are observed in agents during a chain-forming event
6.15	10 min	6.15	6 mm width of micrograph. Bütschli droplets in a complex chain formation	'Protocell roses'
6.16 & 6.17	15 min	6.16 & 6.17	6 mm width of micrograph. Two droplet assemblages merge and suddenly change behaviour and morphology	Phase change behaviour observed during the formation of an assemblage when a 'tipping' point is reached. Such events were observed on separate occasions

whirlpools); and they are also found in living systems. Video footage suggests that the droplet shells are manifolds, rather than chaotic spheres of activity, which burst out of themselves like Russian matryoshka dolls, suggesting that these droplets are in a high-energy state. Some shells suddenly collapse and form crystalline deposits, while others eventually stop splitting and bursting out of themselves and enter a new

Table 6.4: Death – from 0–30 s following addition of 0.2 ml droplet of sodium hydroxide to oil phase

Figure ref.	Time after addition of droplet to oil phase	Movie	Pattern morphology	Comments
6.18	20 min	6.18 & 6.19	300 micron width of micrograph. Fine crystals of sodium oleate accumulate at the oil/water interface	Crystal deposits accrue at the ‘posterior’ pole of the droplet

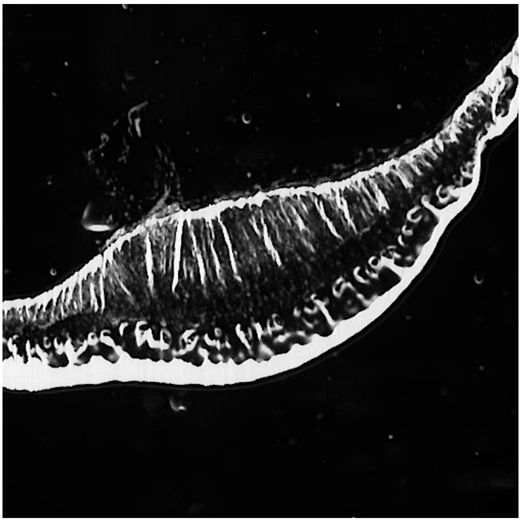

Figure 6.3: The leading edge of the polarized Bütschli droplet field is reminiscent of ‘fire’. Its trailing edge, laced by forming soap crystals, is suggestive of ‘ice’. Micrograph, magnification 4×, Rachel Armstrong, February 2009.

phase of organization as lifelike droplets. It is not possible to predict which shell-like formations, or even what proportion of them, will become self-organizing droplets, as their distribution is outside of the field of view of the microscope.

6.4.3.3 Life: Organizing Droplets

Post chaotic formation phase, the resulting droplets are able to move around, sense their environment, modify their surroundings, produce complex structures and even interact with each other. The interactions and systems are complex and it is not possible to predict the outcomes of the various droplet types. Yet, there are definitive

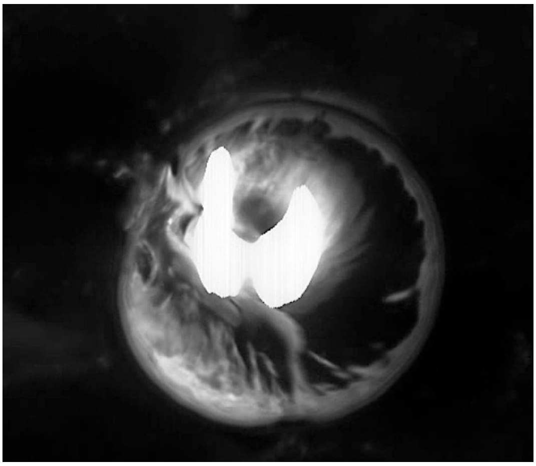

Figure 6.4: Turbulent, shell-like structures are observed at the early, high-energy stages of formation of the Bütschli system. These are indicative of dissipative structure formation, which is characteristic of living systems (Prigogine, 1997). Micrograph, magnification 4×, Rachel Armstrong, February 2009.

patterns of behaviour and interactions that offer a pedagogical view of the system. These characteristics will be discussed in the context of:

- Primary morphologies: Structural characteristics encapsulating the state of the system: droplets, droplets with product, droplet with extended 'osmotic' crystalline structures, polyps, compound structures.
- Primary behaviours: Dynamic interactions that lead to more complex phenomena: interfacing, mirroring, population dynamics.

6.4.3.3.1 Primary Morphologies

The primary morphologies of the Bütschli system are summarized in Table 6.2.

6.4.3.3.1.1 Droplet

The first form that an organized dynamic droplet adopts is a polarized, free-moving droplet, like the one shown in Fig. 6.5, which possesses a fundamental direction partially conferred by its original position in the primary field of 'fire and ice'. Propelled by its primary metabolism, the droplet moves in a given trajectory away from where the original droplet met the oil field, influenced by inhibitors or attractants in the medium, as shown in Movie 6.5. It appears that dynamic droplets modify their surroundings as they pass through a medium (Horibe, Hanczyc and Ikegami, 2011;

Hanczyc, 2011a) and create chemical changes in the field that dynamic droplets sense, which have not yet been characterized.

6.4.3.3.1.2 Droplet with Osmotic Product

Depending on the speed of the chemical reaction and the environmental conditions, a small deposit of crystals appears at the trailing end of the active droplet as the metabolism progresses, as shown in Fig. 6.6 and Movie 6.6. The physical properties of the crystals cause downstream effects on the body of the droplet that influence its locomotion, and ripples can be observed as it drags the gradually increasing load behind the active front. This gives rise to jellyfish or worm-like morphologies and different kinds of movement behaviours such as peristalsis-like locomotion.

6.4.3.3.1.3 Droplet with Extended Osmotic Product

Bütschli droplets undergo progressive physical changes as they continue to consume their primary metabolism and interact with environmental cues, resulting in the production of osmotic microstructures. These are similar in character to the forms Leduc produced on mixing various solutions (Leduc, 1911, p.151), which grow at the trailing end as the droplet moves around the environment. Droplets can also break

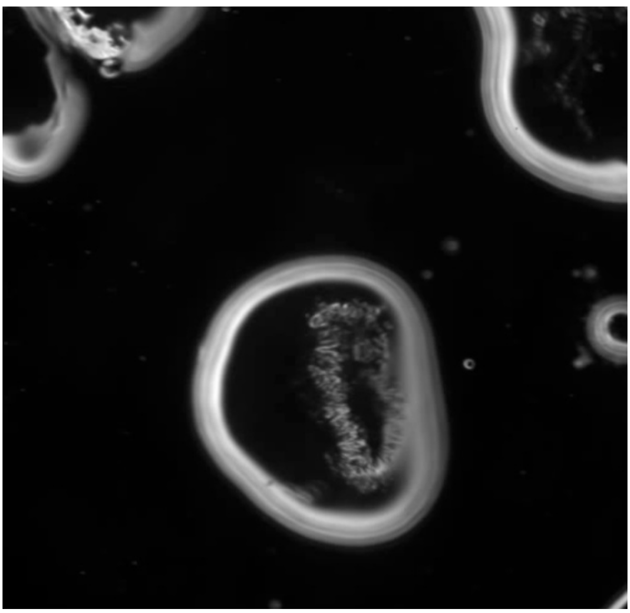

Figure 6.5: Polarized, free-moving droplet. Micrograph, magnification 40×, Rachel Armstrong, February, 2009.

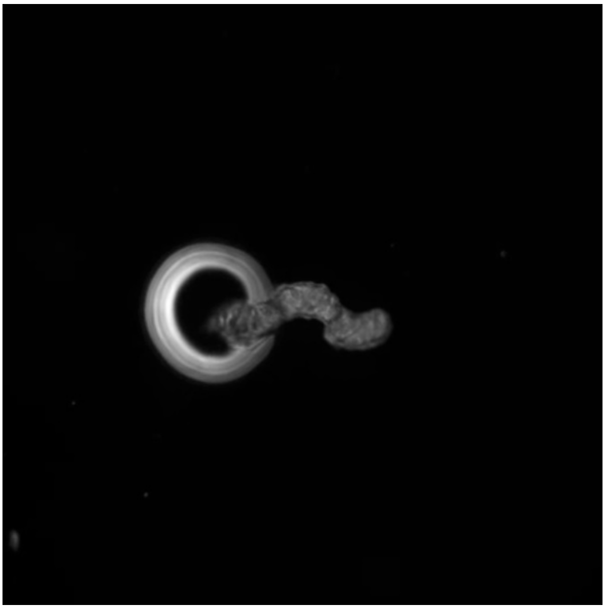

Figure 6.6: Osmotic structures may be produced at the posterior pole of free-moving droplets. Micrograph, magnification 4×, Rachel Armstrong, February 2009.

free from osmotic structures leaving behind them residues that consist of soap crystal 'skins' that are wrapped around an inner core of aqueous (alkaline) media. These structures are visible via fluorescence microscopy, by adding a hydrophilic dye to the droplet at a concentration of 0.25% fluorescein by weight. In Fig. 6.7 and Movie 6.7, a Bütschli droplet deposits a large osmotic residue. When observed under fluorescence microscopy, as in Fig. 6.8 and the latter part of Movie 6.7 (from 1 min 30 s), the fluorescence shows the aqueous phase, which is present in both the residue and the droplet. Bütschli droplets consume themselves as they metabolize and produce soap crystals during this process that travel to the back end of the droplet and accumulate at such a speed and density that they form a tubular, tail-like extension of material.

6.4.3.3.1.4 Microtubes

The character of simple osmotic products may be striking. Under very highly alkaline conditions that approach 4–5 M solutions of sodium hydroxide, the Bütschli droplets respond in a characteristic way in the oil field by producing long, thin, tapering tubes of crystalline product that are shaped by the direction of motion and size of the droplet producing them, as shown in Fig. 6.9 and Movie 6.8.

Figure 6.7: Osmotic casts may be produced by dynamic droplets from which they may break free. Micrograph, magnification 40×, Rachel Armstrong, February 2009.

Figure 6.8: An osmotic cast is observed under fluoroscopy from the droplet in Fig. 6.7, which has been pre-stained using a fluorescent dye (fluorescein 0.01 M at pH 9). The structures are observed under a red light filter to pick up the green light emitted by the stain. The images show that the residual osmotic structures appear to be soap crystal skins that encase an aqueous inner core. Micrograph, magnification 40×, Rachel Armstrong, February 2009.

Figure 6.9: A Bütschli droplet is producing a polyp-like osmotic microstructure. Micrograph, magnification 4×, Rachel Armstrong, February 2009.

6.4.3.3.1.5 Compound Structures

Droplets can produce compound osmotic structures when their bodies fuse and skins combine as a new growth point, as in Fig. 6.10, which was taken from Movie 6.9 at the moment when two Bütschli droplets fused to produce a new growth point for an osmotic structure. The short osmotic structure of one droplet meets a longer branched one to produce a compound microstructure, which is just out of focus. A spiral structure is also clearly visible, which has most likely been produced by another droplet passing through the oil field twisting and advancing simultaneously.

6.4.3.3.2 Primary Behaviours

The primary behaviours of the Bütschli system are summarized in Table 6.3.

6.4.3.3.2.1 Interfacing

Bütschli droplets are chemically attracted to each other and when they meet, they do not usually fuse. Instead, they align their interfaces, producing a very dynamic, oscillating, yet loose relationship between the oil/water boundaries of adjacent

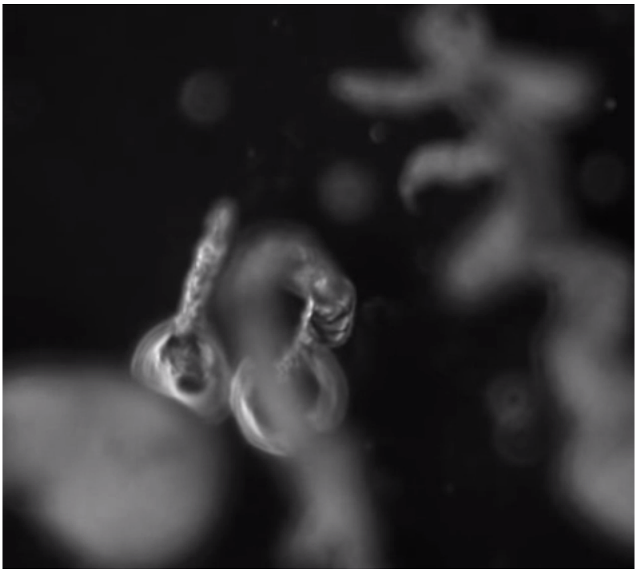

Figure 6.10: Two droplets building microstructures come into close proximity moments before they fuse. Micrograph, magnification 4×, Rachel Armstrong, February 2009.

droplets. These dynamic interface connections seem to exert influence on droplet behaviour and generate different outcomes depending on the number of participating agents. It was not possible to determine the exact number of agents required to produce a systemically different kind of interaction between small and larger groups from these experiments. It is not known if there are specific thresholds, or tipping points, for the emergence of different patterns of interaction. More research is needed to further characterize the observed effects. A more precise delivery system for the production of discrete numbers of droplets, such as 3D printing, is hoped to be useful.
Different kinds of 'interfacing' behaviours are observed:
— Between individuals (2).
— In small groups (3–5).
— With larger populations (6 or more).

Individual droplets moving independently can collect together, forming a shared contact area. The contact zone is unstable and the droplets continually change their interaction points, as they are persistently osculating, as shown in Fig. 6.11 and Movie 6.10, where a small Bütschli droplet is situated between two larger ones, where an active interface exchange is constructed between them. There is another point of contact between the two larger droplets below the small one. In general, Bütschli droplets appear to make multiple points of contact at an interface zone. It is not clear if any material is exchanged during this process, but the intensity of the contact decreases as product builds up and the metabolism, which provides the energy for interaction, runs down.

6.4.3.3.2.2 Mirroring

Bütschli droplets that establish an early connection have been observed to mirror each other's appearance and behaviour. In Fig. 6.12, two agents have established an active interface connection and have produced similar broad-based osmotic structures that anchor them. Smaller droplets appear to be attracted to this site of intense activity and a second site of interfacing has been established between the two large droplets by a smaller one, as shown in Movie 6.11.

6.4.3.3.2.3 Satellites

Bütschli droplets appear to be attracted towards sites of intense metabolism. Large droplets appear to be able to strongly attract smaller ones, resulting in a commonly observed satellite phenomenon where smaller agents frequently orbit larger ones, as shown in Fig. 6.13 and Movie 6.12. It is likely that a product of the primary metabolism is acting as a chemical attractant, though this has not been scientifically verified.

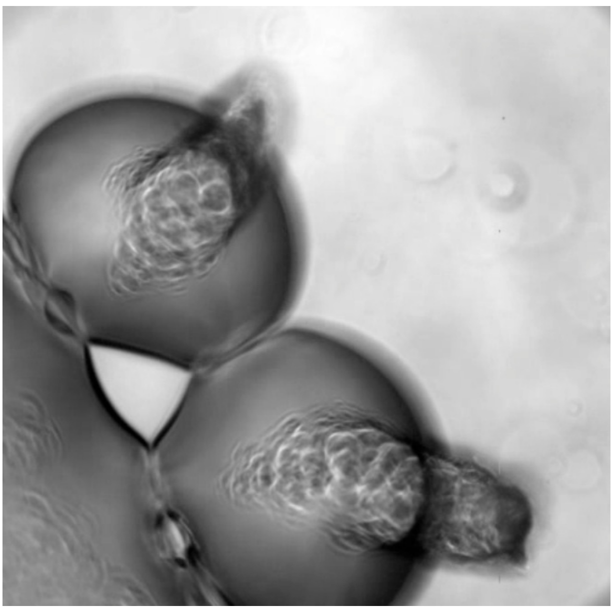

Figure 6.11: High magnification of the active interface between two Bütschli droplets in close proximity. Micrograph, magnification 40×, Rachel Armstrong, February 2009.

Figure 6.12: Bütschli droplets morphologically 'mirroring' each other. Micrograph, magnification 4×, Rachel Armstrong, February 2009.

6.4.3.3.2.4 Chains

Chains of interfacing Bütschli droplets are frequently the first formations that can be seen in the early self-organization process. This occurs where individual droplets have stopped travelling but which are engaged in intense, phased activity at their interfaces with neighbouring droplets. These chains appear to stimulate the metabolism of participating droplets and rapidly encase the active interface with crystals as shown in Fig. 6.14, also in Movie 6.13 and Movie 6.14.

6.4.3.3.2.5 Populations

As Bütschli droplets are drawn towards each other, they form larger populations. They then undergo a range of interactions that result in both a change in the behaviour of the individual agents as well as their appearance. Behavioural changes are likely to occur as the result of metabolic products that attract and/or repel individual droplets as well as the accumulation of product that progressively reduces the amount of available area that the droplets have available as an active interface, as shown in Fig. 6.15 and Movie 6.15. It is likely that a product created by the metabolism causes droplets to be attracted to each other and may be responsible for characteristic emergent behavioural differences observed between small populations (around 2–6 interacting droplets) and larger groups (more than 6 droplets). These numbers are

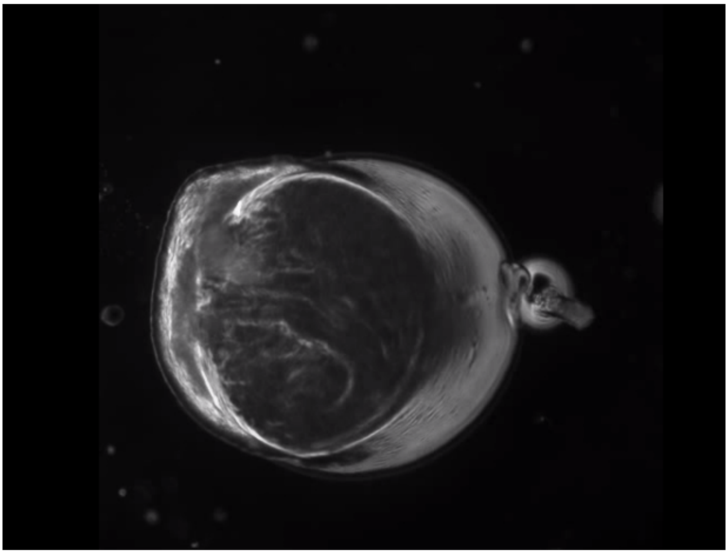

Figure 6.13: Satellite phenomenon, where a smaller Bütschli droplet appears to 'orbit' a large one. Micrograph, magnification 4×, Rachel Armstrong, February 2009.

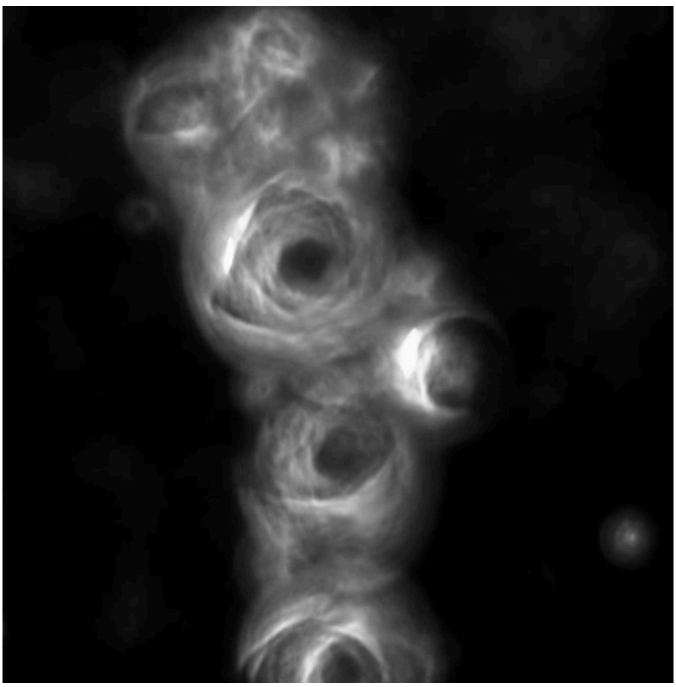

Figure 6.14: A dynamic Bütschli droplet assemblage aligns in a chain-like formation. Micrograph, magnification 4×, Rachel Armstrong, February 2009.

a guideline, based on observation and familiarity of working with the constantly changing system. They are estimated from the frequency of observation of transient, multiple formations of interacting droplets that have been observed during the active phase of the Bütschli system. Finer control of delivery is unlikely to create specificity within this constantly changing system until the Bütschli system itself has been better characterized.

Bütschli droplets appear to possess both attractants/stimulants and inhibitors/repellents of droplet activity. Synchronous group behaviour has been occasionally observed, which results from the recruitment of a number of droplets in proximity. In larger groups, a different, emergent quality has been observed several times, characterized by sudden group behaviours such as scattering, as shown in Fig. 6.16 and Fig. 6.17, as well as Movie S16 and Movie S17, which were independently captured events. These group interactions could be likened to 'quorum' sensing (Nealson, Platt and Hastings, 1970) that occur in certain species of bacteria when, at a threshold number of communicating bacteria, a signal is passed between members and causes a change in the products expressed by the colony. However, unlike quorum sensing where the signal attracts other agents to the site, Bütschli droplets appear to be producing a repellent.

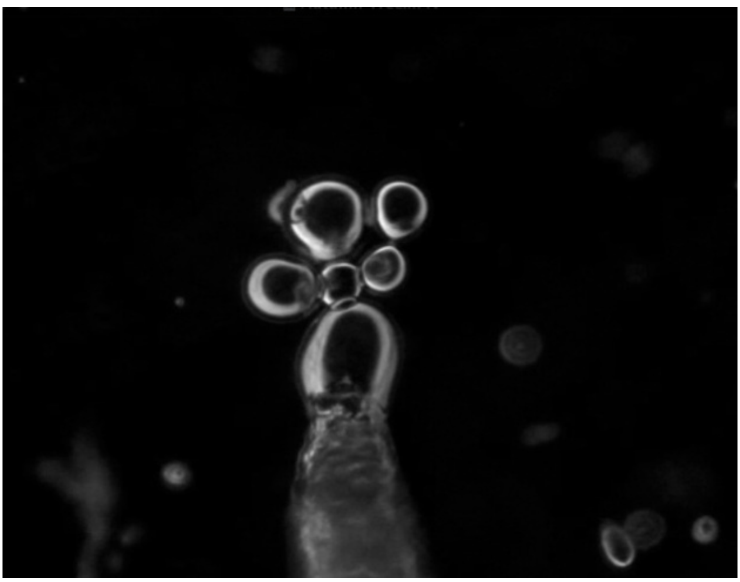

Figure 6.15: Assemblage of dynamic droplets around an osmotic structure. Micrograph, magnification 4×, Rachel Armstrong, February 2009.

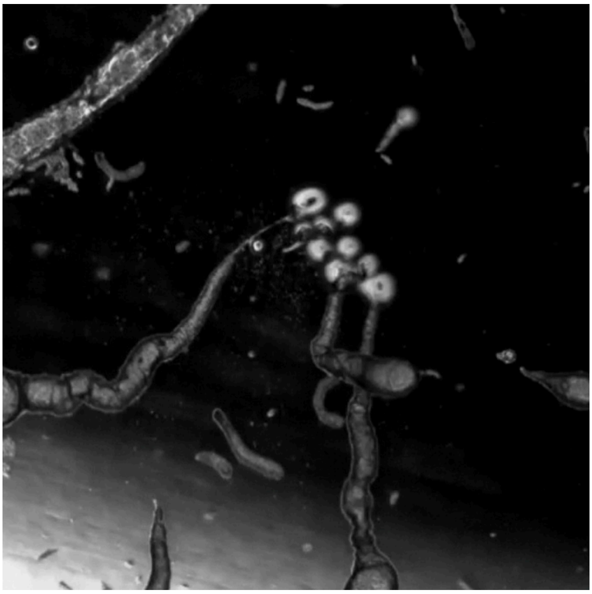

Figure 6.16: Spontaneous phase change in morphology and behaviour in an assemblage of dynamic droplets that reach an unknown chemical 'tipping point' in the system. Micrograph, magnification 4×, Rachel Armstrong, February 2009.

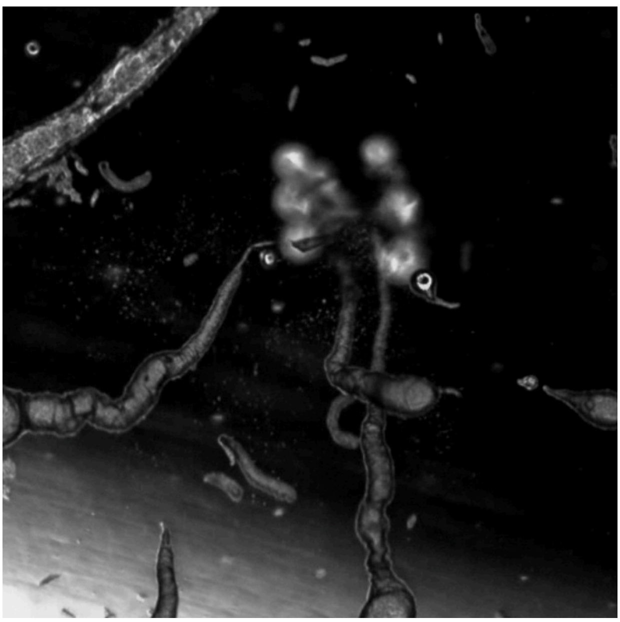

Figure 6.17: A droplet assemblage reaches a chemical 'tipping point' and undergoes a phase change in its morphology and behaviour. Micrograph, magnification 4×, Rachel Armstrong, February 2009.

6.4.3.4 Death: Quiescence

As the metabolism of the Bütschli droplets consumes its body and surroundings, it leaves skins of crystalline materials behind, breaking free of the structures when they produce too much drag. A couple of examples are summarized in Table 6.4. Over time, the metabolism is less vigorous, the droplet moves more slowly and more crystals accumulate over a larger region of the oil/water interface, partially occluding it and reducing the amount of product. The droplet enters a stage of chemical oscillations, where it appears to pulse until it finally stops moving, when all the area available to act as a site of chemical exchange is occluded entirely by crystals. This constitutes a chemical form of ‘death’ as shown in Fig. 6.18, also in Movie 6.18 and Movie 6.19.

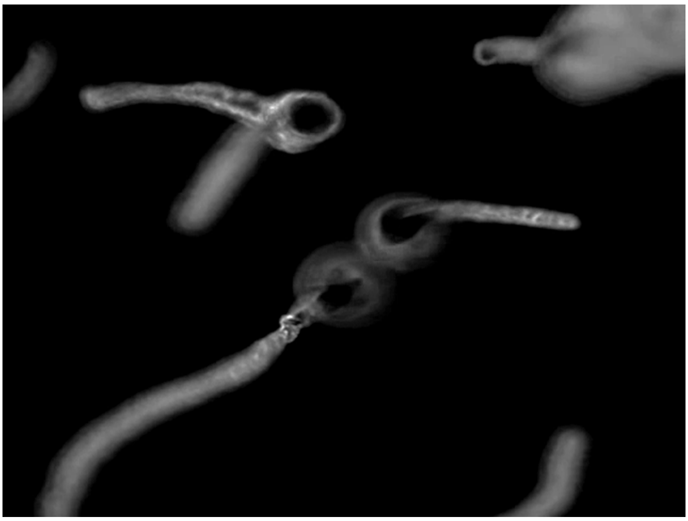

Figure 6.18: Dynamic droplets reach quiescence as their active interfaces are occluded by product. Micrograph, magnification 4×, Rachel Armstrong, February 2009.

6.5 Exploring the Technological Potential of Bütschli Droplets

This section develops the idea of vibrant matter as an alternative production platform to machines with distinctive operational principles. While the language that conveys the technological potential of this platform is well established in the fields of process philosophy (Whitehead, 1979; Agar, 1936; Seibt, 2012), new materialism (Deleuze and Guattari, 1979, pp.3–28) and vibrant matter (Bennett, 2010), the technological capacity has not been explicitly referenced beyond descriptive encounters such as Whitehead’s primordial nature of God (Whitehead, 1979) or Deleuze and Guattari’s creative use of metaphors like rhizomes (Deleuze and Guattari, 1983, p.2).

My research proposed to investigate whether the Bütschli system:
— Could be manipulated using morphological computing techniques
— Provided any unexpected insights into the nature of vibrant matter

6.5.1 Manipulating the Bütschli System Using Morphological Computing Techniques

Having established a set of performance characteristics for the Bütschli system, I designed a series of exploratory experiments that incorporated morphological computing techniques to manipulate the droplets, which are summarized in Table 6.5 and Table 6.6:
— Internal conditions
— External conditions

6.5.1.1 Changing Internal Conditions

Bütschli droplets can be designed to create a range of different products by adding different chemistries to the system, which spontaneously fuse with their bodies. The droplet of aqueous inorganic salt is added to a field of Bütschli droplets and reacts on contact with their alkaline bodies. In this way, the Bütschli droplets can be engineered to make 'secondary' forms and metapatterns (Volk, 1995) that are deposited at the oil/water interface, using different kinds of ingredients. For example, insoluble, magnetic 'magnetite' crystals can be produced within osmotic structures by creating a layer of Bütschli droplets at an interface of olive oil and diethyl phenyl phthalate (DEPP) by adding 0.2 ml drops of iron II/iron III salts prepared according to an aqueous ferrofluid recipe with a molar ratio of $Fe3+:Fe2+$ of 2:1 (Berger et al, 1999) and produce magnetite on fusion. The droplets are at around the same specific gravity as DEPP and may either form crystals within the droplet bodies, or produce organic-looking growths as they pass through them under the influence of gravity. The movement of the droplets through the oil medium and their subsequent interactions produce sculptural forms, as shown in Fig. 6.19 and Table 6.5.

It is of note that the Bütschli droplets produced at an olive oil/DEPP interface do not exhibit lifelike behaviours, as it appears the contact between the droplet and a surface such as glass is a critical ingredient and warrants further investigation. Indeed, when droplets at an olive oil/DEPP interface are observed under 4× magnification, they exhibit disorganized, vigorous movement, which can be seen in Fig. 6.20 and Movie 6.20.

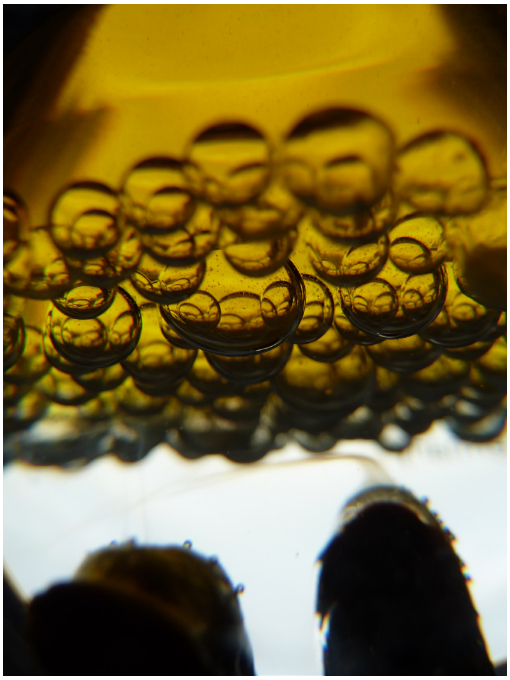

Figure 6.19: Macroscopic view of modified Bütschli droplets following the addition of a 0.2 ml drop of aqueous ferrofluid. Photograph, Rachel Armstrong, February 2009.

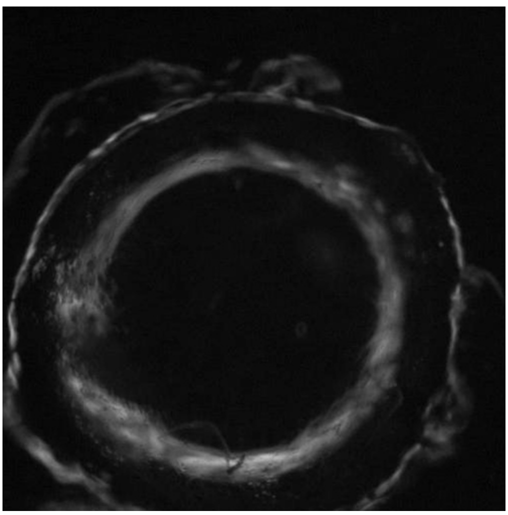

Figure 6.20: Chaotic chemical activity is reminiscent of a 'solar flare' and is observed in the absence of surface contact between the Bütschli system and a solid surface such as glass. Micrograph, magnification 4×, Rachel Armstrong, February 2009.

Table 6.5: Manipulation of Bütschli system: Internal programming

Figure ref.	Time after addition of droplet to oil phase	Description of pattern morphology	Comments
6.19	45 s	Layer of modified Bütschli droplets suspended over 'osmotic stalagmites' composed of iron II and iron III precipitates. 3 cm width of photograph	Macroscopic view of Bütschli system following the addition of a 0.2 ml drop of aqueous iron salt solutions into a modified Bütschli system

Table 6.6: Manipulation of Bütschli system: External programming

Figure ref.	Time after addition of droplet to oil phase	Movie	Description of pattern morphology	Comments
6.20	Any	6.20	6 mm width of photograph. Disorganized chemical activity in the Bütschli system appears like a 'solar flare'	Chaotic chemical activity is observed in absence of surface contact. This appears to play an important role in the emergence of lifelike characteristics
6.21	Any	6.21	6 mm width of photograph. The addition of acetone to the oil field increases droplet aggregation	Droplets vigorously move towards the source of acetone
6.22	Any	6.22	6 mm width of photograph. Ethanol causes rapid movement and agitation of droplets that are short-lived	Droplets migrate rapidly towards the source of ethanol
6.23	Any	6.23	300 micron width of photograph. Droplets appear to form assemblages more readily in the presence of butan-1-ol	Activity appears prolonged in the presence of butan-1-ol

6.5.1.2 Changing External Conditions

Changing the external conditions of the medium alters the behaviour of the Bütschli system and the results from a series of experiments are summarized in Table 6.6. However, the chemical basis of chemotaxis in dynamic droplets has not been established as the whole system is driven by the complex dynamics of composite molecular self-assembly, autonomous movement and interactions between droplets (Toyota, 2009). A series of experiments were conducted to examine the influence on the Bütschli system of organic solvents added to the olive oil field (viscosity 103 mPa at 20°C) (Bürkle GmbH, 2011) such as ethanol, 1-butanol and acetone. These were observed using a Nikon Eclipse TE2000-S inverted microscope with a Photometrics Cascade II 512 camera and in-house software. The chemical basis for the observed complex movement and assemblage formation in the Bütschli system is outside the focus of my research, but warrants further scientific research and analysis. Initial observations are, however, provided here for the following substances:
- Acetone
- Ethanol
- Butan-1-ol
- 2-propanol
- 1-octanol

6.5.1.2.1 Acetone

A 4 cm diameter glass dish of olive oil was prepared and 0.2 ml 3 M sodium hydroxide was added to produce Bütschli droplets. As the field of sodium hydroxide began to spread out and break up into millimetre droplets, 0.2 ml acetone (viscosity 0.3040 mPa at 20°C) (Physical Properties of Liquids, not dated) was added to the field of olive oil by trickling it down the side of the glass dish. The Bütschli droplets responded vigorously to the diffusion wave and rapidly moved towards the high concentration gradient. The spontaneous dynamic activity of the droplets rapidly ceased and their tendency to form assemblages was remarkably increased, which was confirmed by observing the system at 4× and 10× magnification and is shown in Fig. 6.21 and Movie 6.21. Around 25 such preparations were conducted and the spontaneous activity in the system ranged from 30 s to 3 min following the addition of acetone.

As a small molecule, acetone quickly diffuses through the oil field and establishes a polarity in surface tension of the droplets, which may at least contribute to their chemotaxis, as well as locally decreasing the viscosity of the oil field. This may also play a role in the increased tendency for the droplets to aggregate as assemblages, which would imply that the 'interfacing' is at least in part provoked by surface tension dynamics. Also, the acetone can diffuse through the oil field and react with residual sodium hydroxide in the Bütschli droplets. Acetone undergoes the highly vigorous 'aldol condensation' (aldehyde and alcohol) reaction (Nielsen and Houlihan, 1968) in the presence of concentrated sodium hydroxide, to produce ethanal. This vigour may

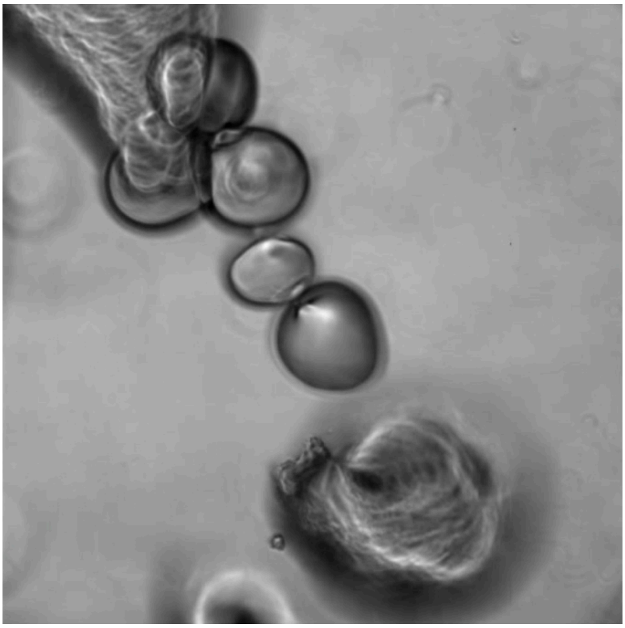

Figure 6.21: Acetone increases droplet aggregation. Micrograph, magnification 40×, Rachel Armstrong, February 2009.

also at least partly account for the system dynamics, which are initially ‘explosive’, then rapidly ‘quenched’.

6.5.1.2.2 Ethanol

A 4 cm diameter glass dish of olive oil was prepared with 3 M sodium hydroxide to produce Bütschli droplets. As the field of sodium hydroxide began to spread out and break up into millimetre droplets, 0.2 ml 100% ethanol (viscosity 1.078 mPa at 20°C) (Physical Properties of Liquids, 2013) was added to the field of olive oil by trickling it down the side of the glass dish. The droplets responded vigorously to the diffusion wave and rapidly moved towards the high concentration gradient. Following vigorous movement towards the source of ethanol, the droplets rapidly formed large assemblages. This grouping, which initially appeared to increase spontaneous dynamic activity of the Bütschli droplets, was rapidly quenched and was observed at 4× and 10× magnification as seen in Fig. 6.22 and Movie 6.22. Around 40 such preparations were conducted and the spontaneous activity in the system ranged from 30 s to 5 min following the addition of butan-1-ol.

As in the case of acetone, ethanol is a small molecule that diffuses rapidly through the olive oil and comes into contact with sodium hydroxide, where it reacts to produce water and sodium ethanoate, which is an ester. However, the ethoxide

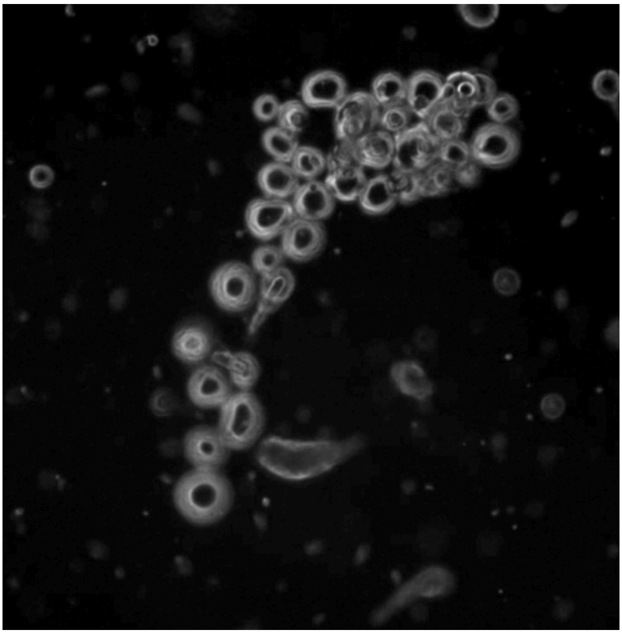

Figure 6.22: Ethanol causes rapid movement and agitation of droplets, which is short-lived. Micrograph, magnification 4×, Rachel Armstrong, February 2009.

ion of the sodium ethanoate also reacts with water, re-forming the alcohol. These are in equilibrium under normal laboratory conditions, so effectively, the net reaction is no reaction because the ethanol re-forms. In the case of ethanol it is possible that the sudden movement is caused by dramatic, polarized changes in surface tension that promote movement of the droplet dynamics but also, perhaps more significantly, by reducing the viscosity of the olive oil. These surface tension changes may be responsible for the increased tendency to form large assemblages, although these observations are speculative and need further formal scientific analysis.

6.5.1.2.3 Butan-1-ol

0.2 ml 3 M sodium hydroxide was added to a 4 cm diameter glass dish of olive oil to produce Bütschli droplets. As the sodium hydroxide field began to spread out and break up into millimetre droplets, 0.2 ml 10% butan-1-ol (viscosity 2.593 mPa at 20°C) (Physical Properties of Liquids, 2013) was added to the field of olive oil by dribbling it down the side of the glass dish. The droplets responded rapidly to the diffusion wave and travelled towards the high concentration gradient, where their spontaneous dynamic behaviour produced small but multiple droplet assemblages. Unlike the cases of acetone and ethanol, the clusters persisted for many minutes before their activity gradually ceased, as seen in Fig. 6.23 and Movie 6.23. This was just visible with the naked eye but was confirmed by observing the system at 4× and 10× magnification. Around 10 such preparations were conducted and the spontaneous activity in the system ranged from 30 s to 20 min following the addition of butan-1-ol.

Butan-1-ol is a fairly small molecule that diffuses through the olive oil and comes into contact with sodium hydroxide, where it reacts to produce water and the ester sodium butyrate. In the case of butan-1-ol, it is possible that the movement is caused by the chemical changes at the droplet surface which speed up the consumption of the sodium hydroxide in the Bütschli droplet, as well as polarized changes in surface tension that promote movement of the droplet dynamics and reduce the viscosity of the olive oil, but less so than the smaller molecules such as acetone and ethanol, so the resultant dynamic changes are less vigorous. These surface tension changes may be responsible for the increased numbers of assemblages observed and their persistence, but these observations are speculative and need further formal scientific analysis.

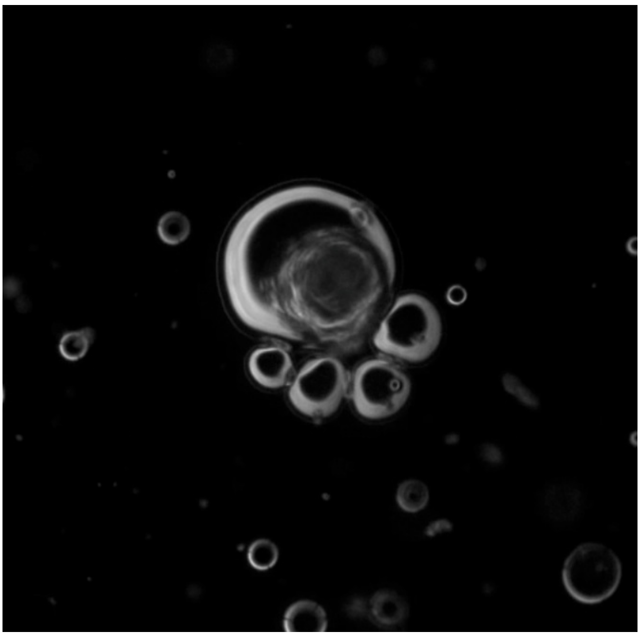

Figure 6.23: Bütschli droplets appear to form assemblages more readily in the presence of butan-1-ol and remain active for longer. Micrograph, magnification 4×, Rachel Armstrong, February 2009.

6.5.1.2.4 2-propanol

0.2 ml 3 M sodium hydroxide was added to a 4 cm diameter glass dish of olive oil to produce Bütschli droplets. As the dissipating field of sodium hydroxide spread out and broke up into millimetre droplets, 0.2 ml 2-propanol (viscosity 2.073 mPa at 20°C) (Physical Properties of Liquids, 2013) was added to the field of olive oil by dropping it down the side of the glass dish. The droplets barely responded to the diffusion wave and little, if no, increased aggregation was observed. The spontaneous activity of the droplets was observed under the microscope at 4× and 10× magnification and appeared to have reduced general activity, although still dynamic. Around five such preparations were conducted and the spontaneous activity in the system ranged from 30 s to 25 min following the addition of 2-propanol.

2-propanol is a relatively small organic molecule that appears to diffuse slowly through the olive oil. It is assumed that, like the other organic solvents, 2-propanol comes into contact with sodium hydroxide, where it reacts to produce water and the ester sodium propanoate. In the case of 2-propanoate, it appears to attenuate the normal activity observed at the droplet surface, which may slow down consumption of the sodium hydroxide in the Bütschli droplet and explains the apparent reduced production of product in the system. Changes in surface tension may also affect the movement of the droplet dynamics by altering the viscosity of the olive oil. These observations are speculative and need further formal scientific analysis.

6.5.1.2.5 1-octanol

Bütschli droplets were produced using 0.2 ml sodium hydroxide in a 4 cm field of olive oil. As the field of sodium hydroxide began to spread out and break up into millimetre droplets, 0.2 ml 1-octanol (viscosity 7.21 mPa at 25°C) (Viswanatha et al, 2007, p.144) was added to the field of olive oil by trickling it down the side of the glass dish. The droplets responded very slowly to the diffusion wave. The spontaneous activity of the droplets was observed under the microscope at 4× and 10× magnification and appeared to have very slightly reduced general activity, although the droplets formed many small clusters and were still dynamic. Around 10 such preparations were conducted and the spontaneous activity in the system ranged from 30 s to 30 min following the addition of 1-octanol.

1-octanol is a fatty alcohol that diffuses slowly through the olive oil, and possesses an amphiphilic character due to its non-polar, lipophilic carbon chain with a polar, hydrophilic hydroxyl group that confers surface activity upon it. Fatty alcohols undergo a wide variety of reactions in the presence of concentrated alkali (Condea, 2000), which is why they are widely used in the soap industry.

6.6 Unexpected Insights Into the Nature of Vibrant Matter

During the research period, the Bütschli system was expected to exhibit interesting qualities relevant to the potential technological performance of the system, which were characterized as follows:
— Locomotion
— Self-replication

6.6.1 Locomotion

The Bütschli system is sensitive to its context and changes its morphology and behaviour in space, time and according to the nature of its metabolism. The forces driving Bütschli pattern formation are therefore different to the formation of bubbles, whose patterns emerge as a consequence of the amphiphilic bilayer interface being supported by internal air pressure and is not fuelled by a specific chemistry. Over their active lifespan, Bütschli droplets may undergo a wide range of changes, where the dynamics of form and movement are entangled. Each actant experiences a different set of forces and conditions that shape the behaviour and morphology of its assemblages. However, the Bütschli system exhibits a minimum complexity, and it has been possible to observe repeatable patterns appearing when both complex systems interact with each other. In Movie 6.6, an individual Bütschli droplet changes its appearance as it grows a crystalline skin at the posterior pole. This causes drag and causes the agent to alter its form of locomotion, since it appears to crawl over the bottom of the petri dish dragging the weight of the crystalline osmotic structure behind it. Indeed, contact between Bütschli droplets and a surface appears to be critical for movement. If a thin layer of dense, clear oil such as DEPP is added to a petri dish, preventing the alkali droplet from touching the base of the container, then the self-organization that drives this behaviour is chaotic and directed movement does not occur, as shown in Fig. 6.20 and Movie 6.20. The degree of plasticity and behavioural change in this system is remarkable, as it does not require any central programming from an organizational molecule such as DNA to initiate this state change. This behaviour suggests that rapid morphological changes without DNA are not only possible but may occur rapidly in systems that possess only a few interacting chemistries, when compared with timescales associated with more complex biological ones.

6.6.2 Self-replication

The Bütschli system does not replicate, and although droplets are observed to divide and fuse, they do pass any specific chemical information to other droplets such as nucleotide polymers that can replicate. This adds more intrigue to the indeterminate identity of Bütschli droplets between living and non-living states, as they have a very low degree of autonomy. Their technological potential is therefore very susceptible to human and non-human influences, as well as requiring significant infrastructural support.

6.7 Summary of Findings Related to the Technological Potential of the Bütschli System

The continuing search for increasingly lifelike materials in the practice of the built environment raises new opportunities in the development of the ELT portfolio. Materials that can deal with continual real-time changes in their surroundings by harnessing living properties, without needing to be pre-programmed with an all-embracing palette of future possibilities, raises the possibility of exploring the production of qualitatively different kinds of spatial program and design tactics in the production of space. The analysis of the Bütschli droplets suggests that this rudimentary chemical system offers a potentially rich, experimental platform, not only for artificial life investigations but also for possible real-world applications of vibrant matter in architectural practice. Enabled by the parallel processing capabilities of chemical systems, Bütschli droplets may simultaneously respond to multiple, overlapping chemical programs that produce behavioural effects such as chemotaxis, attraction or repulsion and morphological outcomes such as the production of casts, tails or sculptural formations. Such opportunities also present new architectural and technological challenges, which require an understanding of how it is possible to spatialize chemical programs and design with emergent phenomena.

As a technology, the self-organizing Bütschli system exhibits a recognizable series of chemical patterns that result from the process of saponification and are visible to the naked eye. Closer examination under the microscope provides further information about the morphology of the chemical waves that shape the evolution of the droplets. The technological potential of the system exists during the lively phase of the reaction (which exists from between 30 s and 30 min after formation), when the droplets are sensitive to chemical and physical fluctuations in their surroundings. For example, during this phase, Bütschli droplets can produce spatially distributed mineral deposits with sculptural qualities when they come into contact with discrete chemistries such as aqueous ferrofluids. It is anticipated that applying precision-guided devices, such as 3D modelling software coupled to 3D printing devices, will provide opportunities to design and engineer with bottom-up chemical solutions to provide a development platform for dynamic, chemistry-based ELT (Adams, 2012) with potential architectural applications. Yet, the actions of Bütschli droplets can be orchestrated by manipulating flows of chemical information and instructed to consume or produce selectively in a given environment, as shown with other droplet systems (Hanczyc, 2007).

Bütschli droplets embody the principles of assemblage formation that underpin the effects of vibrant matter through population-scale behaviour and in resisting fusion with adjacent droplets through dynamic boundary interactions (Latour, 1996; Deleuze and Guattari, 1979; Bennett, 2010). This study suggested that interacting droplets exhibit as yet uncharacterized chemical periodicity through cycles of attraction and repulsion at the oil/water interface. This appears to maintain the 'body' of the assemblage by preventing even densely packed groups of agents from fusing. The periodic 'interfacing' between Bütschli droplets also enables them to remain mobile and sensitive to environmental changes. Additionally, it appears that assemblage formation in these systems can be induced by the addition of organic solvents to the olive oil field, except for 2-propanol, although this requires further testing since the sample size was small. Yet, these initial observations are intriguing and, ultimately, may be valuable in understanding how to orchestrate complex technologies. Indeed, as lifelike, chemically programmable delivery systems for a variety of materials that can also respond to environmental conditions, Bütschli droplets may have future real-world applications that are relevant to the practice of the built environment, such as smart paints, or surface coatings with the potential to fix carbon dioxide into inorganic carbonate in response to environmental cues (Armstrong, 2010d; Armstrong, 2011b). From a technological viewpoint, the Bütschli droplet system provides a model system that is sufficiently robust to begin to establish a set of design and engineering principles that could be used in architectural design practice.

It is envisaged that droplet technology may also become part of a larger production process suggested in recent work at the University of Oxford by Gabriel Villar and colleagues, who used vesicles within a 3D printing system to form microscale structures (Villar, Graham and Bayley, 2013) and also by Klaus Peter Zauner's group at the University of Southampton, who are producing dynamic vesicle systems through microfluidics devices (University of Southampton, not dated; Palmer, 2010).

6.8 Bütschli Droplets as a Potential Drawing Technology

> *... what I am searching for is a way to turn ... a mode of analysis into one of synthesis.*
> (Kipnis and Leeser, 1997, p.8)

The technological potential of Bütschli droplets was explored with the context of drawing practice tactics forged through collaboration between human and non-human codesigners, as an 'ecology of drawing'. While there is no formal definition for drawing, the practice requires coherence, integrity and artfulness (Kimmelman, 1992). Sigmund Abeles viewed drawing as a 'touching at a distance' where human desire is entangled with physical experience. These remote and immediate relationships form networks of interactions that engage the technological potential of the material realm and converge in the production of a material effect that may be read as a drawing. The use of dynamic droplets in the practice of drawing relates to a long history of spontaneous forms of drawing where matter possesses various degrees of non-human agency. For example, acheiropoieta, like the Turin shroud (Charney, 2012), and automatic drawing processes, such as exquisite cadavers and frottage, engage the material realm beyond direct human conscious control. The traces produced from the interactions between the assemblages may be culturally interpreted and ascribed meaning as drawings.

Dynamic droplets constitute a 'wet' drawing method where both medium and traces evolve during the production process. Such practices are in keeping with water-based printing where pigments are distributed over the surface of water using soaps and stains and lifting them on to paper, as well as – in Xandra van der Eijk's self-drawing process – where paint is dropped down a pendulum to produce a wet, continuous, self-organizing drawing (Van der Eijk, 2013). They also forge a direct relationship with the physical world that is directly expressed as an 'ecology' of interactions. Dynamic droplets may also be considered as a form of prototyping, with functional similarities to 3D (Armstrong, 2012g) and 4D (TED.com, 2013b) printing processes (where wet materials are processed into 'dry' media), rapid prototyping (where resinous materials are cast into 'dry' forms) and film-based photography (where chemistry and light capture a moment of complex interior and exterior relations). Since dynamic droplets do not exist in the natural world, their engagement in a drawing process is a deliberate intervention precipitated by a human agent. Therefore, the artistic pursuit within the drawing system is in establishing the conditions for the drawing and then shaping the subsequent interactions. The quality of recordings are influenced by the medium and the chemistry of the agents, where drawings are produced through casts and chemical traces as non-linear graphical recordings, which also have a sculptural quality. They may either be left to follow their own trajectory, or chemically persuaded to adopt new behaviours and trajectories by adding chemical cues. This method of drawing production can be likened to a form of frottage, where otherwise invisible chemical landscapes are graphically revealed through the production of material traces. Dynamic droplet drawings observe a very proximate relationship between agents that are expressed at the molecular level through chemical encounters. In this manner, the droplet draws by revealing invisible cues present in the environment with a level of sensitivity and precision that cannot be apprehended directly by the human senses. By viewing the dynamic droplets as a technological extension of our body – similarly to the way a hammer exerts the force that a body can exert on its surroundings, or how Google Glass goggles enable us to experience virtual spaces in the real world – then dynamic droplets may also be thought of as an extended sensory system that enables us to graphically read molecular palimpsests in our surroundings (Armstrong, 2012b). Although we cannot see these relationships, the experience provides us with the kind of sensory detail that exceeds the capabilities of our unaided vision. Dynamic droplet recordings are 3D soft, wet, 'osmotic' skins that can be seen with the naked eye as residues that produce unconventional, dissipative geometries and evanescent structures during their trajectories. Since the Bütschli system is effectively 'closed', most of the dynamic droplet drawing activity reaches equilibrium between 30 s and 30 min, during which time they reveal chemical information in landscapes from the microscale to the megascale. After several hours, unmodified Bütschli droplets gradually dissipate and decay into a fine, soapy precipitate in the petri dish.

When Bütschli dynamic droplets are used as drawing agents, they produce a variety of outputs whose limits may be established by a human designer by altering the internal and external conditions of the system using morphological computing techniques. Architects working with dynamic droplets produce drawings through a continuous process by shaping the conditions in which the emergence of a drawing is increasingly likely. Each drawing is unique and moulded by the internal and local conditions to produce traces that are emergent, contingent and permanent. The following drawings in Figs. 6.24–6.27 offer some examples of the graphical range of the system.

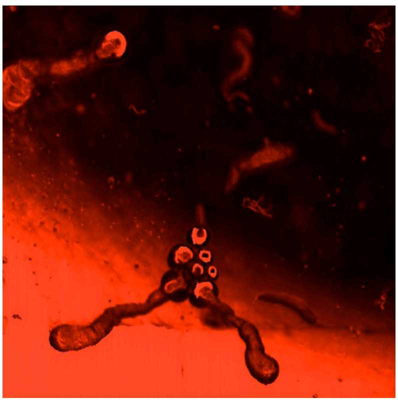

Figure 6.24: Landscape produced by droplet assemblages. Micrograph, magnification 4×, Rachel Armstrong, February 2010.

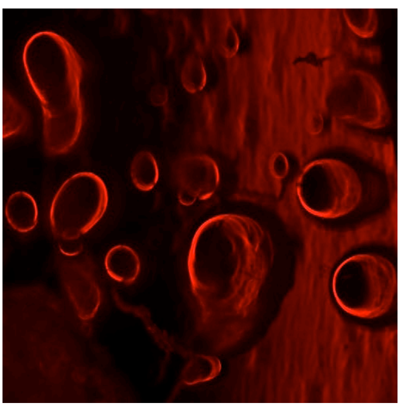

Figure 6.25: Landscape produced by droplet assemblages. Micrograph, magnification 4×, Rachel Armstrong, February 2010.

Figure 6.26: Organic structures composed of osmotic skins produced by droplet assemblages. Micrograph, magnification 4×, Rachel Armstrong, February 2010.

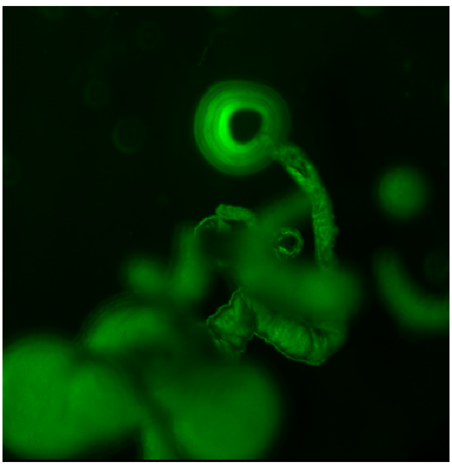

Figure 6.27: Landscape produced by droplet assemblages. Micrograph, magnification 4×, Rachel Armstrong, February 2010.

Dynamic droplet drawings summon improbable forms into existence and provoke new juxtapositions between agents to reveal hidden chemical landscapes. Although the technique is at an early stage of development, the co-development of 3D printing as a delivery platform for these agents may offer architects greater precision when setting up drawing fields. Such potential convergence may give rise to new design and drawing platforms that can further articulate 'ecologies of drawings'. Potentially these combined platforms could provide new materials, methods and technologies that enable architects to effectively design more adeptly with probabilistic systems.

6.9 Ontological and Epistemological Issues Raised by Bütschli Droplets

The Bütschli system potentially offers a new technological platform that exhibits non-classical behaviours that invoke a distinct set of concepts that are different to those of machines and can be practically demonstrated through the formation of chemical assemblages. As an expression of vibrant matter, Bütschli droplets pose a particular challenge to the structuring of knowledge. The complexity, organizational diversity, extreme environmental responsiveness and physical entanglements with other ontologically distinct systems, such as machines, means that trying to describe the potential of the Bütschli system within a portfolio of architectural design tactics is not only a constantly moving physical target, but a conceptual one too! While Bütschli droplets may be framed within the language of process philosophy and scientifically characterized through the principles of complexity, observing the system is inevitably mired in linguistic and aesthetic expectations (Morton, 2007). This makes it difficult to view and describe the constantly changing Bütschli system without trying to establish its performance within pre-existing knowledge sets. Yet this is exactly what needs to be done if the full potential of this emerging technology is to be fully explored and imagined. Indeed, the Bütschli system may yet prove to be ‘post-epistemological’, or unclassifiable in any coherent, meaningful way using traditional modes of classification such as the Linnæan system (Latour, 2013).

Although man-made, and in that sense ‘artificial’, the lifelike performance of the Bütschli system provides an opportunity to consider the emergent characteristics as a subset of living qualities in order to construct a more thorough understanding of the system as a whole. However, there is no classification system to characterize dynamic lifelike chemistries. Yet, Carl Linnæus imposed an order on natural systems that included three domains, animal, vegetable and mineral, which therefore embraced both living and non-living materials and facilitated a comparative understanding of these systems by appreciating similarities and differences (Linnæus, 1735). Of interest is Linnæus’ taxonomy of stones, which he asserted possessed some of the properties of living things. In particular, Linnaeus asserted that stones grew by way of an accretion process, such as when sand aggregated and became sandstone, or when the apparent clumping of clay particles formed limestone. He also included the formation of quartz in his classification system, which he proposed was due to a ‘parasitic’ mechanism. However, minerals were dropped from taxonomic classification during the 18th century and are absent from Lamarck’s 1809 classification scheme, *Zoological Philosophy* (Lamarck, 1999), which focuses exclusively on the cataloguing of animals. Additionally, Ernst Haeckel’s famous 1866 ‘Tree of Life’ (Haeckel, 1866) based on Charles Darwin’s taxonomic diagram (Darwin, 1859) equated phylogeny with the story of evolution and excluded the mineral world from phylogenetic ordering systems. It is possible that the omission of minerals from a scientific ordering of the natural world may also have been influenced, at least in part, by the popularization of Louis Pasteur's germ theory (Pasteur, 1866), which refuted a widespread belief in spontaneous generation, where life was thought to be created directly from inert matter (Armstrong and Hanczyc, 2013).

The approach taken in reporting the observations is relevant to current systems of classification used in biology and natural history, which may help to relate non-living phenomena to biological systems through a description of the pattern morphology. There is much to be learned through comparative analysis and my research attempts not only to observe, but also to construct, an understanding of the characteristic of the lifelike properties of the Bütschli system as the basis for further study. An examination of this system also aims to establish some guiding features and principles that also identify its potential for development towards ELT.

Conventionally, dynamic systems are described by recognizing geometric domains within them such as patterns and metapatterns. Yet, there are semantic problems with such an approach, since pattern recognition, through identifying particular kinds of morphology, reveals nothing about the process of production, which is closer to an algorithm that represents a set of rules than any particular geometry, which encapsulates one particular time frame in a sequence of events. For example, complex structures such as the cephalopod and mammalian eye (Serb and Eernisse, 2008) may result from convergent evolution of structures (Doolittle, 1994). Additionally, very similar patterns may be generated within different media, such as DNA-producing mollusc shells (physical systems) and the graphical modelling of shell-like structures on a computer screen (virtual systems) (Tyson, 1994). Moreover, there is semantic and philosophical incongruity in the very practice of using 'geometric' criteria as the conceptual framework for non-linear systems, since they are ontologically distinct.

Ideas that are consistent with an idea of 'process ontology' may be used to observe and interpret the experimental findings of the Bütschli system, as a way of characterizing a potential non-linear epistemology. The aim is not to formalize an approach but to begin to reflect upon the possible systems of reference for the development of non-linear technologies. The hope is that subsequent descriptions, expectations and criteria for success, may not be unconsciously constrained by the expectations of working with machines. Matt Lee uses the term 'oceanic ontology' to refer to the 'contingency of being that relies upon an empiricist property of the sensible as a continuous, connected and open whole' (Lee, 2011, p.14), which is inspired by Friedrich Nietzsche's ontology of forces, being photographically represented in Fig. 6.28.

Oceanic ontology produces maps rather than theories of concepts (Lee, 2011, p.27) and can be understood as an emergent process, which 'produces a model – both implicitly and explicitly, of the process, of which it is a part' (Lee, 2011, p.44). The importance of using a unique ontology is to embody the ideas that it represents. For example, Manuel DeLanda proposes that complexity and non-linear dynamics have shaped human civilization. He rereads human history to examine this idea by embodying the feedback loops and organizing fields that he proposes has shaped

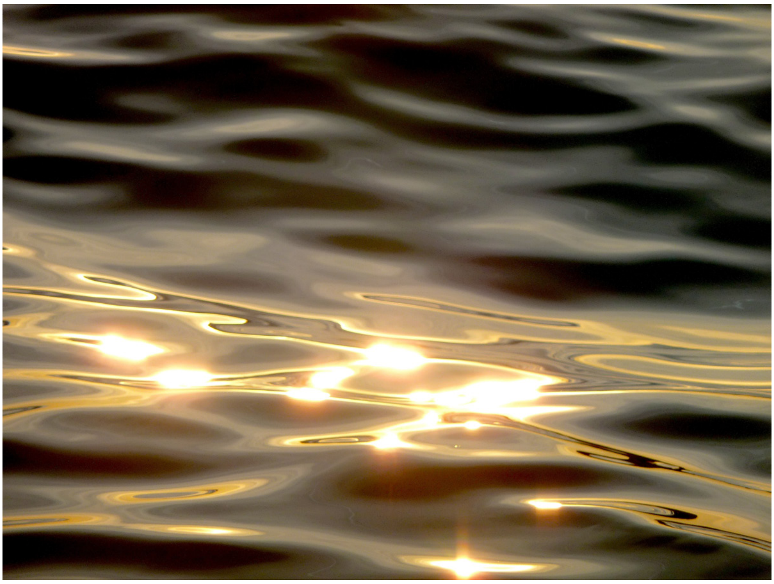

Figure 6.28: The changeable nature of oceanic landscapes is revealed by this photographic recording of the complex interplay between light, wind and water on the surface of the Venetian lagoon. Photograph, Rachel Armstrong, August 2012.

our culture. For example, he views the development of (unplanned) cities as 'arising from the flow of matter-energy' that inhabit a variety of flows and constraints as 'self-organised meshworks of diverse elements' (DeLanda, 2000, p.32) Similarly, the Bütschli system may literally and/or figuratively provide of a way of reading events of transformation that are related to non-linear fields of action, rather than a series of any particular events caused by specific individuals or agents. The pedagogical challenges of such complex systems may benefit from reading unfolding events through an oceanic ontology that does not require the observer to choose between fields of action, local events, or actors as organizing hubs of activity, but can simultaneously consider them. Lee proposes that the process of knowledge acquisition within non-linear systems can be studied through actors (Lee, 2011, pp.27–28). While ANT (Latour, 1996) refers to the agency of elements, which may be human or non-human, as 'actors', Lee takes the idea literally and observes how thespians can make sense of highly unstable environments, which may be a play, stage or text. 'The actor presents us with … a way of learning … that isn't subject centred but created through the movement of transformation … that opens a space of process that is a form of understanding but one radically distinct from the subject centred model' (Lee, 2011, p.130). This idea may be applied to the Bütschli system, where dynamic droplets may be considered as 'actors' within a constantly changing, non-linear field of chemical activity. The interactions between different actors, and also with their complex environment, produces events that leave physical traces which help construct a reading of the ‘plot’, which may be considered as a form of (micro)architecture having been produced by the events within a space on an ‘ever-changing stage’ (Tschumi, 2012, p.28).

An oceanic ontology of Bütschli droplets was constructed, in collaboration with Simone Ferracina, by viewing them as actors that simultaneously embody ‘space, event and movement’ (Tschumi, 2012, p.28) within their complex chemical fields of activity. Drawing from Tschumi’s notion that relationships are what give architecture meaning, a diagram was produced (see Fig. 6.29) which represents the contextualization of (meta)events between actors (droplets) with time within a complex field of activity. The stage is not a single reading of events but reflects multiple possibilities where the ‘plot’, or field of activity, is constructed through exploratory, graphical approaches. The resultant diagram maps relationships in the system rather than invoking the classical ‘tree’ metaphor of classification systems, which focuses on differences rather than similarities between actors.

The graphic is centred at time zero, from which concentric circles radiate, representing an exponentially increasing series of time intervals. This logarithmically increasing function encapsulates the intense self-organizing activity that happens early on in the chemical reaction and falls off rapidly with the passage of time. An

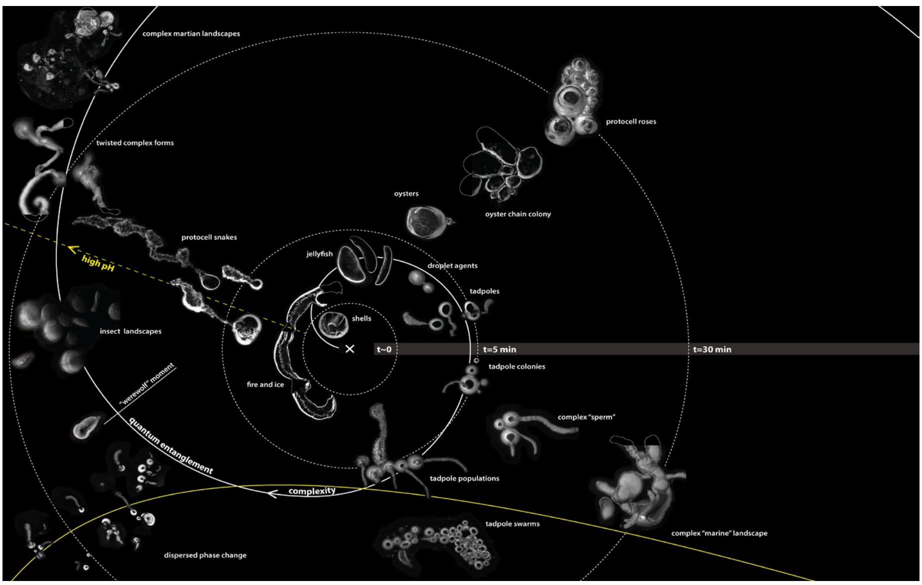

Figure 6.29: This diagram depicts dynamic droplets as ‘actors’ that operate within the many variable influences encountered in their oil field as an ontolological ‘map’ of events. While the diagram is drawn as a 2D topology, the possible events within the field are manifold and open up multidimensional spaces through their interactions with continuous, multiple contingencies that shape the evolution of the system. Diagram designed by Rachel Armstrong and drawn by Simone Ferracina, July 2012.

estimated 90% of chemical activity is completed within five minutes of activation of the system, although individual droplets have been observed to be active as long as an hour after their genesis. A spiral that represents complexity also radiates from the origin and depicts the high frequency of events around the start of the reaction, which become less frequent as time unfolds. The various morphologies and behaviours that indicate change in the system are grouped subjectively according to the authors' experimental findings and interpretations. For example, the complex oyster chains are distinct in appearance but only differ in degree from the complex marine landscapes. Specifically, 'oysters' produce a large mass of material and their soft bodies bulge from their material shell-like tethers, which anchor them, as shown in Fig. 6.30.

In contrast, 'marine landscapes' are composed of a variety of largely inert forms that have been produced by droplets that would previously have been described as 'oysters'. However, the undulating droplets are long gone, leaving only a trail of residues behind them, as in Fig. 6.31.

The diagram also indicates the impact of chance events from a source external to the system, such as an incidental trajectory that intersects with the fundamental progressive vectors of the Bütschli system. It represents disturbances in the environment, like changes in ambient temperature, or physical disturbances. This external vector also touches the spiral of complexity and, in this case, may cause agents within the system to reach tipping points.

The diagram also employs metaphor to convey dynamic qualities and complex

Figure 6.30: Oyster-like, thick, osmotic structure produced by dynamic droplets. Micrograph, magnification 40×, Rachel Armstrong, February 2009.

Figure 6.31: Thick, osmotic structures being produced by dynamic droplets that are moving away from their deposits and producing 'marine landscapes'. Micrograph, magnification 4×, Rachel Armstrong, February 2009.

attributes of the Bütschli system. For example, the 'werewolf moment' is a droplet event that is characterized by extreme agitation and simultaneous rapid production of residue, which gives the agent a rather 'hairy' appearance. This striking event is most likely precipitated by the ratio between droplet surface area and the volume of the droplet that is optimized and therefore rapidly consumes the dynamic agent. The rapid precipitation of product over the droplet surface causes drag that precipitates erratic movement in the system owing to the uneven distribution of surface deposits. The chemical excitement phase typically lasts for around a few minutes as it produces a large amount of residue that is swept to the posterior end of the droplet by molecular action and physical forces, where it is suggestive of a 'tail'. This structure contributes to the physical changes in the system as it exerts a great deal of drag on the system. These complex events immediately precede droplet inertia as the dense precipitation extinguishes the droplet metabolism by completely occluding the interface.

6.10 Observations Made with Respect to the Ontology and Epistemological Issues of Bütschli Droplets

Drawing from my experimental observations and insights gained during mapping the oceanic ontology of the Bütschli system, the following observations were made:

- Oceanic ontologies are not tools to solve specific challenges through a process of reductive thinking, but may be useful pedagogies to build assemblages of relationships or concepts (Lee, 2011, p.27) which help navigate complex challenges and terrains.
- A process-based, oceanic ontology may help characterize events within the complex chemical system to free observations from our expectations. Additionally, use of the spiral of complexity (rather than the traditional tree metaphor, or more recent notion of a web, which is a very complex version of a tree), enables the system to be epistemologically described and imagined beyond a comparative analysis of geometric patterns and metapatterns. The idea of a structure unfolding and folding back on itself as a navigational instrument creates a space of possibility in which relationships between and similarities within the system may relate, connect and potentially construct new kinds of knowledge.
- By working with the poetics of the system in the production of a diagram, oceanic ontologies may provide a pedagogical framework that enables disciplinary convergence across the Two Cultures (Snow, 1959) and ultimately, the development of technological species that 'synthesize[s] quantities into qualities' (Ambasz, 2006, p.22).
- An epistemological progression of events through actors within an oceanic ontology is an informal exploration, not a formal classification system, and needs to be further explored and interrogated.
- Although metaphorical descriptions are inexact (i.e. non-geometric) assessments of the system, they may, however, help establish multidisciplinary and collaborative approaches in conveying complex ideas. This is problematic in a scientific context, where important issues such as repeatability, quantification, precision, rigour and the effective communication of ideas must be respected as intrinsic to the field. However, in the arts and humanities the value of metaphor is in curating sets of ideas and their cultural expression. Oceanic ontologies therefore provide a means of exploring different conceptual frameworks to develop an accessible language through which multiple disciplines may work as an 'ecology' of practices (Stengers, 2000), by identifying convergences within seemingly divergent practices and ultimately create opportunities for synthesizing new approaches in design and engineering with non-linear systems.
- Further exploration of the possible applications of oceanic ontologies and maps would be informative in assessing the transferability of the approach. For example, in a scientific context, oceanic ontologies could be used as a graphical version of a Turing test (Cronin et al, 2006), where complex events may be

visually compared. Parallax between the systems under observation may provide new information that may (re)inform further experiments, but this is beyond this particular research inquiry.

The innate flexibility, pluripotency and context sensitivity of oceanic ontologies confers them with the ability to find synergies between different frameworks. Indeed, they may prove essential in enabling designers to simultaneously inhabit object-oriented and process-led systems, which may be key to developing new modes of architectural design practice. As Whitehead observes, both Heraclitean and Platonic perspectives are useful in the process of knowledge acquisition and are entangled in our experience of them.

> *Ideals fashion themselves round these two notions, permanence and flux. In the inescapable flux, there is something that abides; in the overwhelming permanence, there is an element that escapes into flux. Permanence can be snatched only out of flux; and the passing moment can find its adequate intensity only by its submission to permanence. Those who would disjoin the two elements can find no interpretation of patent facts. ... But the two elements must not really be disjoined ... bodily life transmits itself as an element of novelty throughout the avenues of the body. Its sole use to the body is its vivid originality: it is the organ of novelty*. (Whitehead, 1979, pp.339–340)

6.11 Summary

Materials at far from equilibrium states appear to embody the principles of vibrant matter through the production of assemblages, with the potential to forge a new kind of technological platform. These principles were demonstrated by conducting a range of 300 replicate experiments on the Bütschli system, which provided both a material system and a technology that could build and even enhance relationships between populations of agents and their surroundings. Using the Bütschli droplet system it was demonstrated that vibrant matter:
- Possesses agency
- Can be programmed using morphological computing techniques
- Provides unexpected insights into the behaviour of non-linear technology

These experiments suggest that vibrant matter may be applied within the engineering and construction of buildings as ELT. Potentially new relationships may be orchestrated by applying these technologies that result in the production of architecture, which builds ecological connections within systems. Depending on how ELT is imagined and designed, strategic applications may even remediate, absorb or make use of environmental toxins, for example, by incorporating them in the repair and growth of materials (Armstrong, 2012b). Most importantly, ELT promotes new ways of ‘seeing’ design and architectural solutions that no longer rely on machine metaphors. This technological platform enables us to imagine and express the world anew, with the potential to build new relationships with our environment and produce new kinds of knowledge. In this context, the role of the architect is as codesigner within ecologies of actants, all of which are establishing claims in a material system. Acts of codesign are therefore equivalent to acts of 'life', which refuse to accept deterministic pathways that are forged by past events, or obey the limits imposed by the claims of other actants in the system. Instead, by embracing the role of 'vibrant' architect, codesigners respond to constraints within the system through acts of continual creativity.

To meaningfully develop the principles and possible practices of vibrant matter, ELT must be accessible at the human scale. In the following chapter, I aim to test the scalability of dynamic droplets and other lively chemistries in an architectural design context.